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A comprehensive review of solar facades. Opaque solar facades

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ABSTRACT

In antiquity, people already knew the principles of solar architecture, designing their houses to the south to take advantage of the sun in all seasons. Today, solar architecture is undergoing a true revolution because of the development, among other things, of special facades involved in the processes of heating, ventilation, thermal isolation, shading, electricity generation and lighting of homes: these are called "solar facades". This paper aims to review the remarkable developments that have occurred during the first decade of this century in this field.

Contents

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1. Introduction

In his *Memorabilia*, Xenophon reports that the perfect house for Socrates should "have a southern aspect, sunshine during winter will steal in under the verandah, but in summer, when the sun traverses a path right over our heads, the roof will afford an agreeable shade . . ." Today, the same fundamental principles apply as they did 25 centuries ago, but with vast improvement in the scientific progress over this period.

In architecture, a facade is by general definition, the outer envelope of a dwelling's living space, which is located vertically in most cases. The facade, in addition to its aesthetic function, must satisfy other requirements: being waterproof, insulating the interior thermally and acoustically and in some cases being fire resistant.

Today solar architecture is undergoing a true revolution because of the development among others, of solar facades designed for heating, ventilation, thermal isolation, shading, electricity generation and lighting of buildings. Fig. 1 illustrates their general classification.

This paper aims to review the remarkable scientific studies carried out during the first decade of this century in solar facades, specifically the opaque solar facades all over the world. A quantitative summary of the literature reviewed is shown in Fig. 2.

The literature reviewed, within each of the systems mentioned below, was separated into (Fig. 2c) theoretical and experimental studies, development studies, feasibility studies and applications, thereby facilitating any future literature review intended to be done on the subject treated in this work.

2. Opaque and active solar facades

The opaque solar facades absorb and reflect the incident solar radiation but cannot transfer directly solar heat gain into the building. When such opaque solar facades transform the incident sunlight into electricity for immediate use or for transmitting the thermal energy into the building by the use of electrical or mechanical equipment (pumps, fans, valves, control equipments), then they are called opaque and active solar facades.

2.1. Building-integrated solar thermal (BIST) system

A building-integrated solar thermal (BIST) system for facades can be conceived as the application of solar collection equipment to the facade of a building so that the equipment performs the function of an envelope while it simultaneously collects solar energy for heating purposes (Fig. 3).

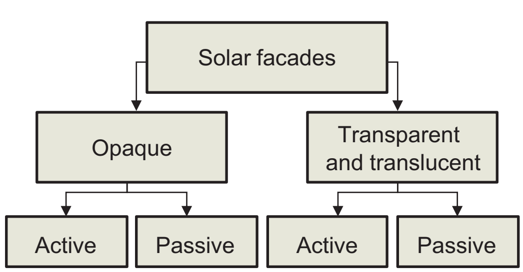


Fig. 1. Solar facades classification.

2.1.1. Theoretical and experimental study

Van Decker et al. [1] measured the heat exchange efficiency of an unglazed transpired solar collector (UTSC) for the case where the plate is perforated with circular holes on either a square or triangular lattice, covering a range of wind speeds extending from zero to 5 m/s. A predictive model, based on breaking down the total heat transfer into contributions from each of the plate sections, was developed: the front, the holes and the back. The model matched the observation with a precision of 4.2% root mean squared error.

Fleck et al. [2] carried out an experimental study on an unglazed transpired solar collector to measure the effects of wind direction, speed and fluctuation intensity. The monitoring system included instruments to measure temperatures, collector outlet flow rates, solar radiation, wind speed, and wind direction, as well as an ultrasonic anemometer placed near the centre of the collector. Their observations indicated a high degree of turbulence near the wall which feeds the near wall region and that peak collector efficiency occurred at non-zero wind speeds between 1 and 2 m/s.

Gunnewiek et al. [3] analyzed the flow distribution of air through the face of an UTSC, taking into account the presence of wind. Various building orientations were examined at a wind speed of 5 m/s. The wind was found to reinforce those factors that tend to produce outflow, and in light of this study, the recommended minimum average suction velocity required to avoid such outflow has been raised from about 0.0125 m/s to about 0.03 m/s, depending on the building shape.

Leon and Kumar [4] presented the details of a mathematical model for an UTSC using heat transfer expressions for the collector components, and empirical relations for estimating the various heat transfer coefficients. It predicted the thermal performance over a wide range of design and operating conditions. The parametric studies were carried out by varying the porosity, airflow rate, solar radiation, and solar absorptivity/thermal emissivity, and finding their influence on collector efficiency, heat exchange effectiveness, air temperature rise and useful heat delivered. Results indicated that solar absorptivity, collector pitch, and airflow rate have the strongest effect on collector heat exchange effectiveness as well as efficiency. The results of the model have been used to develop nomograms, which can be a valuable tool for a collector designer in optimising the design and thermal performance of UTSC.

Boutin and Gosselin [5] studied numerically a vertical open-ended channel, such as a solar wall, filled with a porous medium, with an imposed heat flux and a heat loss coefficient on one of its walls. Correlations are developed for optimal pressure drop to be imposed by the fan and maximal energy recovery, as a function of the Rayleigh number, the channel aspect ratio, and the heat loss coefficient.

Richman and Pressnail [6] modelled, using an analytical model and seasonal simulation, the performance of a solar dynamic buffer zone (SDBZ) within a curtain wall system. Solar dynamic buffer zone is a low cost method for gathering solar energy efficiently by using the movement of air. Given the example design conditions, the analysis showed that the SDBZ can act to replace up to 90% of required fresh air for a typical mid-rise commercial building while significantly reducing the cost by preheating during daytime hours. Considering the need for experimental studies, Richman and Pressnail [7] conducted a laboratory investigation to quantify the performance of the SDBZ. Results from the experimental

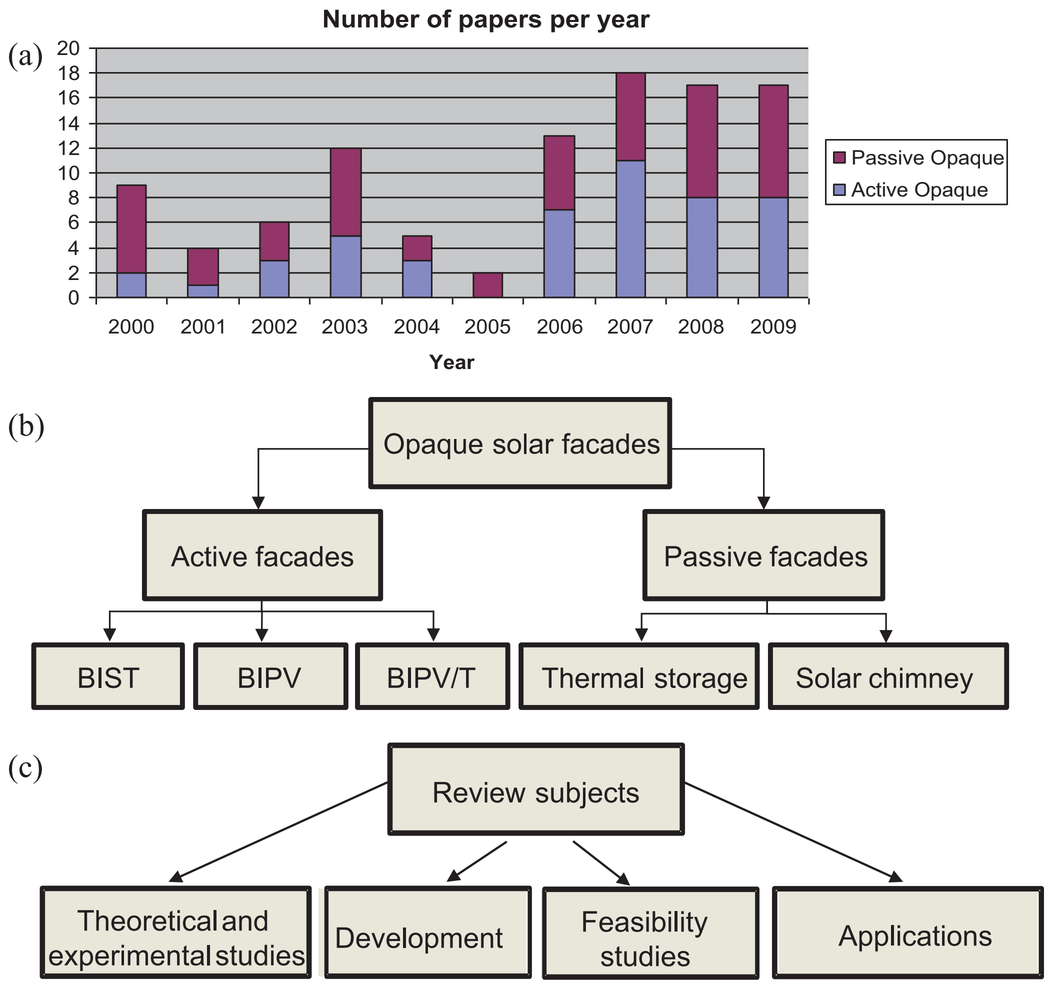


Fig. 2. Content of the review: (a) journal papers distribution per year; (b) review classification; (c) review specific subjects.

testing were used to validate a one-dimensional numerical model of the prototype. Experimental efficiencies of 25–30% were recorded, placing this system in the middle of published efficiency ranges for solar air collectors.

2.1.2. Development

Orel et al. [8] formulated and prepared a variety of polyurethane-based thickness insensitive spectrally selective (TISS) paints for practical utilization as paints for coloured unglazed solar absorbers. Efficiency for photo-thermal conversion of solar radiation was assessed by evaluation of the corresponding performance criteria, which enabled the selection of paints whose performance criteria values were higher than 0 (spectrally non-selective black coating). Results showed that the green and blue coloured aluminium flake pigments were essential for achieving simultaneously positive PC values and chroma values (chroma is the quality that distinguishes the colour from the grey shade) between 7 and 27. They also suggested to avoid copper flake pigments because of their inferior corrosion resistance.

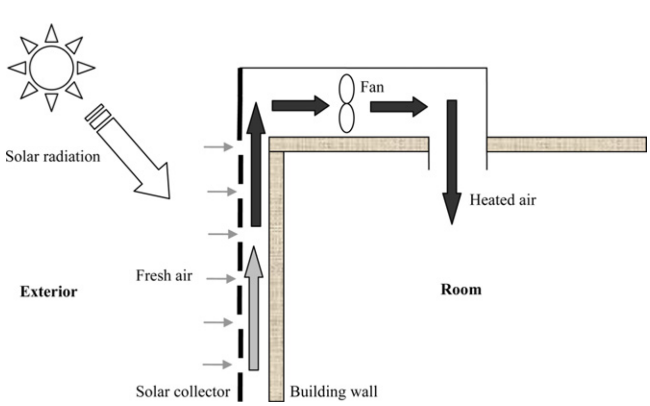


Fig. 3. Schematic diagram of building-integrated solar thermal system (e.g., unglazed transpired solar collector).

Japelj et al. [9] prepared an organic–inorganic nanocomposite via sol–gel processing from 3-(trimethoxysilyl)propylmethacrylate and titanium(IV) isopropoxide precursors (TiMEMO) in the form of a viscous resin, and used it as a binder for the preparation of TISS paints and corresponding solar absorber coatings. The surface properties of the non-pigmented TiMEMO binder and the ensuing TISS paint coatings were determined from contact angle measurements. The results showed that the water contact angles of non-pigmented TiMEMO binder increased from 70° to 125–135° for the corresponding pigmented TISS paint coatings. They suggested to measure the long-term stability of these novel hybrid materials for application in TISS paint coatings for solar facade collector systems. Later, Kozelj et al. [10] studied the formation of a protective layer from (3-mercaptopropyl)trimethoxysilane (MPTMS) on commercial Sunselect® (a TISS coating) for unglazed collector systems. The protective layer imparted corrosion stability to Sunselect® in a salt spray chamber for at least 20 days. The most important finding

was that the applied MPTMS layer did not affect the spectral selectivity, as the solar absorbance increased only by 1% and thermal emittance by not more than 2%.

Jerman et al. [11] developed a TISS paint coating made of fluoropolymer resin binder (Lumiflon (LF), Asahi Glass Co., Ltd., Japan) for unglazed solar facade absorbers. The TISS paint coatings studied in this work were spectrally selective and they repelled water and oils.

2.1.3. Feasibility study

Ubertini and Desideri [12] described the research and development activities concerning a solar air collector suited for winter heating and summer ventilation, which was installed at the scientific high school in Umbertide, in central Italy. The collector physical and numerical modelling of heat transfer and fluid flow in winter operation is presented. The system performance has been estimated as a function of different parameters in order to provide a tool for the design process. Furthermore, the climate in the area has been simulated based upon the available meteorological data and the system behaviour under these conditions was presented. The solar air collector studied has shown to have good performance as an auxiliary heating system and predicted exit air temperatures during most of the winter exceed 20 °C.

Fraisse et al. [13] studied a wall with an integrated solar air collector and a heavy ventilated internal wall for a timber frame house, in France. Their main purpose was to develop a system, which aims at reducing the energy demands and improving thermal comfort in summer. The transmission of solar energy to an internal concrete cavity wall by air is analyzed. They selected a closed loop air circulation because, with an air to air heat exchanger, it could be proved to be more effective and the risk of unhealthy air pollution is reduced.

Munari Probst and Roecker [14] presented and commented the results of a large internet survey on architectural quality of existing building integrated solar thermal systems addressed to more than 170 European architects and other building professionals. Subsequently, a novel methodology to design future solar thermal collectors systems suited to building integration and to ensure both energy efficiency and architectural integrability (size, shape, colour, etc.) has been proposed.

Hernández et al. [15] presented the design, modelling and computational simulation of solar air heaters installed at the first bioclimatic hospital of Argentina, located in Susques. They gave details on the materials and dimensions of solar air heaters made of V-corrugated black metal plates. They developed a specific simulation program for the modelling of the solar air heaters. With this software, the sizes of the heaters, their air outlet temperatures and the useful energy generated were determined and daily efficiencies of 67% were obtained.

2.2. Building integrated photovoltaic (BIPV) system

Henemann [16] defines a building integrated photovoltaic (BIPV) system as photovoltaic cells which can be integrated into the building envelope as part of the building structure, and therefore can replace conventional building materials, rather than being installed afterwards. The beauty of BIPV lies in the name: it can be used in any external building surface. Rather than sticking out like a sore thumb, BIPV modules can be naturally blended into the design of the building, creating a harmonious architecture. Also, as an added benefit, air flow behind the solar cell reduces their temperature which improves their efficiency and longevity (Fig. 4).

2.2.1. Theoretical and experimental study

Brinkworth et al. [17] derived a simplified method to estimate the flow rate in naturally ventilated photovoltaic cladding for buildings. This method is based on a one-dimensional loop analysis in which the buoyancy forces are balanced by the pressure drops due to friction. Wind effects at the entrance and exit are also taken into account. The hypothesis tested is that the form and values for the friction factors and internal heat transfer coefficients for the buoyancy driven case are the same as those for forced convection in ducts. Overall excellent agreement between the modelled and measured mass flow rates is obtained. A general model is then derived to describe the thermal behaviour of building integrated PV with natural ventilation cooling for use in a wide variety of design and validation exercises.

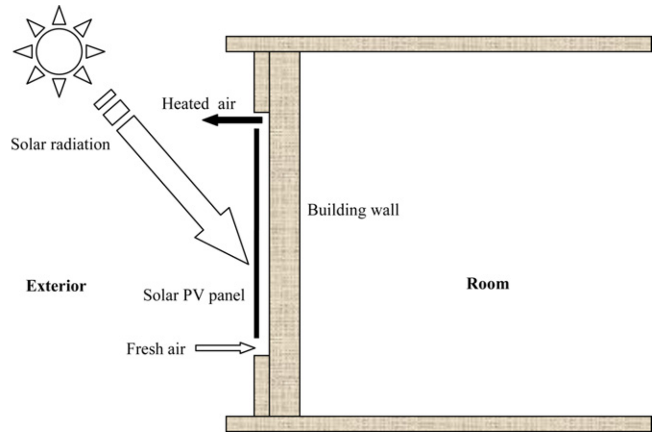


Fig. 4. Schematic diagram of building integrated photovoltaic system.

Yang et al. [18] investigated the heat transfer across a photovoltaic wall to determine the cooling load component contributed by building-integrated PV walls. Calculation results showed that the cooling load component could be obtained conveniently by using the average outdoor temperature and recommended film coefficients of the special building claddings. The meteorological data of three cities (Hong Kong, Shanghai and Beijing) were used as examples to calculate the heat gains and the cooling load components of typical building walls. Comparing with the results between PV walls and massive walls, the photovoltaic integration in building walls reduced the corresponding cooling load components by 33–50%.

Chow et al. [19] described a comparative study of three different options in applying large-scale building-integrated PV technology in a coastal city at the South China Sea. The computational model was based on a 260 m^2 mono-crystalline silicon PV wall part of a 30-storey hotel building. The numerical analysis used the ESP-r building energy simulation software, developed at the University of Strathclyde. The results showed that the different design options exhibit short-term electrical performance differences, but have similar long-term electricity yields.

Huang et al. [20] investigated by experiments and numerical simulations the use of a phase change material to moderate BIPV temperature rise. A parametric study of a design application is also reported. Temperatures, velocity fields and vortex formation within the system were predicted for a variety of configurations using a numerical model validated by experimental measurements. Temperature distributions predicted for different insolation and ambient temperatures at the photovoltaic surface show that the moderation of temperature achieved can lead to significant improvements in the operational efficiency of photovoltaic facades. In a subsequent work, Huang et al. [21] presented an experimental evaluation of phase change materials (PCM) for thermal management of photovoltaic devices. Two particular phase change materials were used to moderate the temperature rise of photovoltaic panel. The thermal performance of different internal

fin arrangements for improving bulk PCM thermal conductivity was presented. Using Rubitherm® 25 with internal fins, the temperature rise of the PV/PCM system can be reduced by more than 30 °C when compared with the datum of a single flat aluminium plate during phase change. They recommended the realization of an economic and environmental impact analysis for the developed technology to determine the potential benefits from specific levels of market penetration.

Bloem et al. [22] presented the assessment of experimental data for electrical and thermal performance evaluation of photovoltaic systems integrated as cladding components into the building envelope. An improved design for a common test reference environment has been developed. The study concluded that a dedicated experimental outdoor set-up for building integrated PV applications will provide the necessary information to develop a calculation model for BIPV systems in the built environment.

Fossa et al. [23] carried out an experimental study on natural convection in an open channel to investigate the effect of the geometrical configuration of heat sources on the heat transfer behaviour. The objective of the work was to investigate the physical mechanisms which influence the thermal behaviour of a double-skin PV facade. Different heating configurations were analyzed, including the uniform heating mode and two different configurations of non-uniform and alternate heating. The heat transfer coefficients were inferred and recast in dimensionless form. The results in terms of wall temperatures showed that the effect of increasing the channel spacing is to reduce, on an average base, the working temperatures for all the three heating modes investigated.

Jiménez et al. [24] presented a method for linear or non-linear continuous time modelling of physical systems using discrete time data. As a case study, the thermal characteristics of a building-integrated PV component were considered. Four poly-crystalline PV modules were tested under different real weather conditions. The ventilated airflow in the gap behind the PV module and the radiative exchange between the PV module and the facing wall was changed also. A non-linear first order stochastic differential equation has been found to be the most appropriate to describe the heat transfer of the PV component.

Friling et al. [25] studied in detail the influence of forced ventilation with fins in the air gap of a building integrated photovoltaic application. They considered an experimental set-up which aims to remove heat from the PV module and its boundaries for increasing electricity production efficiency. The analysis has revealed that it is necessary to use non-linear state space to obtain a satisfactory description of the PV module temperature. In these systems, the heat transfer was increased with the forced ventilation velocity, while the type of air flow did not have a striking influence. The residual analysis showed that the best description of the PV module temperature is obtained when fins, disturbing the laminar flow and making it turbulent, are applied in the set-up combined with high level of air flow. The improved description by the model is mainly seen in periods with high solar radiation.

2.2.2. Development

Maurus et al. [26] described several attractive features of implementing thin-film technology based on amorphous silicon (a-Si) for building-integrated photovoltaic installations. They also presented some BIPV examples.

Mallick et al. [27] carried out a comparative experimental characterisation of an asymmetric compound parabolic photovoltaic concentrator (ACPPVC-50) suitable for vertical building facade integration in the United Kingdom along with its non-concentrating counterpart. The measured average solar cell temperature of the PV in the concentrator system was only 12 °C higher than that of the similar non-concentrating system with same cell area. The results showed that the use of the ACPPVC-50 system increased the maximum power by 62% for a geometrical concentration ratio of 2.0 with the same incident solar radiation compared to a similar non-concentrating PV panel.

2.2.3. Feasibility study

Jie et al. [28] presented a detailed simulation model for a PV-wall structure with different integration modes (with and without ventilation), based on the weather data in Hong Kong. The influence of different integration modes on the annual power output and heat gain was discussed. They concluded that the PV-wall with ventilation had a very little improvement on the power output. However, the PV-wall with ventilation could reduce much heat gain in comparison with that without ventilation.

Ordenes et al. [29] analysed the potential of seven BIPV technologies implemented in a residential prototype simulated in three different cities in Brazil (Natal, Brasília and Florianópolis). Simulations were performed using the software tool EnergyPlus (developed jointly by Lawrence Berkeley National Laboratory, the University of Illinois, the U.S. Army Construction Engineering Research Laboratory, GARD Analytics, Inc., Oklahoma State University and others.) to integrate PV power supply with building energy demand (domestic equipment and heating, ventilating, and air conditioning systems). The building model is a typical low-cost residential building for middle-class families, as massively constructed all over the country. Results presented an interesting potential for decentralized PV power supply even for vertical surfaces at low-latitude sites. In general, for 30% of the year, photovoltaic systems generated more energy than building demand.

Abu-Rub et al. [30] studied the feasibility of cladding high-rise towers in Doha with solar photovoltaic modules. Specifically, the case of the Qatar Financial Centre is discussed. The major aim of the work was to evaluate the technical feasibility, economic impact and environmental effects of using photovoltaic panels on commercial towers in Qatar. Numerical calculation was done using solar pathfinder software. The study showed that the PV system would produce an estimated 62,082 kWh/year for the present configuration of the QFC tower, a saving estimated of $2360 and a corresponding saving of 33,334 tonnes of CO_2 emissions annually.

2.2.4. Application example

Omer et al. [31] presented monitored results of two examples of building integrated PV systems investigated at the School of the Built Environment, University of Nottingham in the UK. One of the systems was installed on an educational building, and consisted of a thin film PV facade appropriate for commercial or office suites. The work undertaken during this project identified a number of difficulties at different stages of the design, installation, commissioning and operation of the BIPV systems.

Yang et al. [32] investigated a number of issues on the first building-integrated photovoltaic system in Hong Kong. Simulation and data monitoring have been completed for energy performance of the BIPV system under the local weather conditions. The natural ventilation effect of an air gap on PV module's power output and heat transfer across the PV wall has been investigated.

Marsh [33] presented an analysis about R&D efforts and progress of building integrated photovoltaic systems in Europe and North America. Successful examples of R&D activities and applications of crystalline silicon, thin compound solar materials and polymer conducting materials in BIPV were analyzed.

2.3. Building-integrated photovoltaic thermal (BIPV/T) system

A building integrated photovoltaic thermal (BIPV/T) system combines the functions of a building integrated photovoltaic system with those of a building-integrated solar thermal system. This combination seeks to achieve a most efficient use of a solar

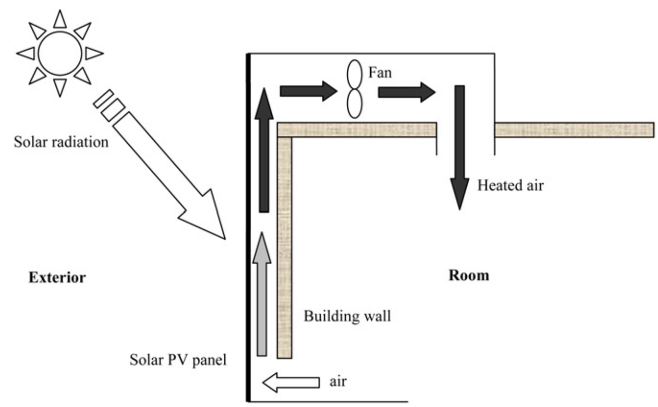


Fig. 5. Schematic diagram of building-integrated photovoltaic thermal system (BIPV/T).

energy-collecting surface in terms of both an optimal electrical conversion and air/water heating (Fig. 5).

2.3.1. Theoretical and experimental study

Ji et al. [34] developed a numerical model of a wall-mounted hybrid photovoltaic/water-heating collector system by modifying the Hottel–Whillier model, which was originally for the thermal analysis of flat-plate solar thermal collectors. Computer simulation was performed to analyze the system performances. The combined effects of the solar cell packing factor and the water mass flow rate on the thermal and electrical efficiencies were investigated. The simulation results indicated that an optimum water mass flow rate existed in the system through which the desirable integrated energy performance can be achieved.

Muresan et al. [35] studied the integration of a combined photovoltaic-thermal collector as a component of building facades. They detailed the models describing conduction and radiation heat transfer in a PV module, which govern the thermo-aerodynamics in the air channel. In the case of a vertical channel heated at one side, a parametric study is performed as a function of the channel width, wall heat flux, and dimensionless turbulent intensity. A preliminary application of the coupled radiation—the natural convection heat transfer problem corresponding to a photovoltaic-thermal collector configuration—is proposed.

Chow et al. [36] described an experimental study of a centralized photovoltaic and hot water collector wall system that can serve as a water pre-heating system. Collectors are mounted at vertical facades. Different operating modes were performed with measurements in different seasons. Natural water circulation was found more preferable than forced circulation in this hybrid solar collector system. The thermal efficiency was found to be 38.9% at zero reduced temperature, and the corresponding electricity conversion efficiency was 8.56%, during the late summer of Hong Kong. Suggestions were provided on how to further improve the system performance.

Jie et al. [37] established a two-dimensional model of PV glass panel and a model of the PV-Trombe wall system. Results showed that according to the measured weather data and the special simulation condition, the temperature difference between the elements with and without PV cell on the glass panel reached a maximum value of 10.6 °C; the temperature difference between the room with and without PV-Trombe wall reached a maximum value of 12.3 °C during 3 days. In a following study, Jie et al. [38] investigated a PV-Trombe wall (PV-TW) installed in a fenestrated room with heat storage. Based on an updated mathematical model, theoretical simulation has been conducted for PV-TW in this case. From the view of field testing, a significant indoor temperature increase with a maximum of 7.7 °C has been obtained, with respect to the reference room. Since the natural convection induced by the original PV-TW was insufficient, Jie et al. [39] presented a novel PV-Trombe wall assisted with direct current fan. A significant temperature increase of indoor temperature with a maximum of 14.42 °C was obtained. Meanwhile, the experimental average electrical efficiency of the PV-TW assisted with fan could reach 10–11%.

Tonui and Tripanagnostopoulos [40,41] investigated the performance of two low cost heat extraction improvement modifications in the channel of a photovoltaic/thermal (PVT) air system to achieve higher thermal output and PV cooling so as to keep the electrical efficiency at acceptable level. The use of thin flat metal sheet suspended at the middle or finned back wall of an air channel in the PVT air configuration was the suggested method. Both experimental and theoretical results showed that the suggested modifications improve the performance of the PVT air system. In a subsequent study, Tonui and Tripanagnostopoulos [42] presented the air cooling of a commercial PV module configured as PVT air solar collector by natural flow. A numerical model was developed and validated against the experimental data obtained from outdoor test campaigns for both glazed and unglazed PVT prototypes studied. These results showed good agreement between predicted values and measured data and thus could be used to study analytically the performances of these PVT air collectors with respect to several design and operation parameters.

Dehra [43] developed a two dimensional thermal network model in a mathematical programming environment using MathCAD^{TM}. The network model is able to predict the local wall and air temperature in the photovoltaic solar wall installed in an outdoor room laboratory in Concordia University, Montréal. The proposed thermal network model is tested under operating condition of fan-induced hybrid ventilation with mixed convection heat transfer along with radiation heat transfer between photovoltaic module and back panel in the test section and/or with non-homogeneous boundary conditions. The proposed model is also useful for accurately predicting ventilation air requirements for ducts used in photovoltaic hybrid systems for combined supply of electricity and heat.

2.3.2. Development

Radziemska [44] gave a general analysis of results and reviews of applications for building integrated PV/thermal systems. Air and water cooled hybrid photovoltaic-thermal solar collectors were reported. These included prospective applications of amorphous silicon solar module on flexible plastic film and thin film solar cells.

Tripanagnostopoulos [45] presented a new type of PVT collector with dual heat extraction operation, either with water or with air circulation. This system is simple and suitable for building integration, providing hot water or air depending on the season and the thermal needs of the building. Experiments with dual type PVT models of alternative arrangement of the water and the air heat exchanging elements were performed. The most effective design was further studied, applying to it the following three modifications for the air heat extraction improvement: the interposition of a thin metallic sheet (TMS) element in the air channel (PVT/dual-TMS model), the mounting of the fins (PVT/dual-FIN model) on the opposite air channel wall and the combination of TMS with roughened opposite channel wall by small ribs (PVT/dual-TMS/RIB model).

Zondag [46] presented an overview of a large amount of research on PVT collectors carried out over the last 30 years, both in terms of historic overview of research projects and in the form of a thematic overview, addressing the different research issues for PVT.

Hasan and Sumathy [47] made a review of the available literature covering the latest module aspects of different photovoltaic/thermal collectors and their performances in terms of electrical as well as thermal output. The review covers detailed

description of flat-plate and concentrating PVT systems, using liquid or air as the working fluid, numerical model analysis, experimental work and qualitative evaluation of thermal and electrical output.

Norton et al. [48] reviewed the recent research in building integrated photovoltaic with the emphases on a range of key systems whose improvement would be likely to lead to improved solar energy conversion efficiency and/or economic viability. Several developments of a BIPV facade acting as a water and air-heating collector were also discussed.

Chow [49] made a review of development trends of the technology, in particular, the advancements in recent years and the future work required.

2.3.3. Feasibility study

Ji et al. [50] presented a computational thermal model that has been used for analyzing the annual performance of facade-integrated hybrid photovoltaic/thermal collector system for use in residential buildings of Hong Kong. In the study, the applications of EPV (film cell) and BPV (single silicon cell) panels in this hybrid photovoltaic/hot-water system were investigated. Simulation results based on test reference year data showed that the annual average electrical efficiencies of the hybrid EPV and BPV modules were, 4.3% and 10.3%, respectively, the corresponding annual average thermal efficiencies to hot water were 47.6% and 43.2%, and, compared with a normal concrete wall, the reductions of space heat gain in summer season through the collector wall were 52.9% and 59.1%. The annual overall energetic efficiencies were 58.9% and 70.3% respectively, which are much better than the conventional solar collector performance.

Crawford et al. [51] combined two different photovoltaic cell types with a heat recovery unit and analysed them in terms of their life-cycle energy consumption to determine the energy payback period. Energy payback periods between 4 and 16.5 years were found, depending on the BIPV system.

Guiavarch and Peuportier [52] developed a model for building integrated photovoltaic systems and implemented it in a dynamic simulation tool. The influence of the type of integration upon the PV and hybrid PV/air collector efficiency has been evaluated. A case study has been performed on two different typical buildings. When the PV collector was used to preheat the ventilation air, the global efficiency (electricity + heat) reached 20%.

Chow et al. [53] showed, through computer simulation, that the photovoltaic/water-heating system has many economical advantages over the conventional PV installation in Hong Kong. The system thermal performance under natural water convection was better than in the pump-circulation mode. For a specific system, a vertical wall of a fully air-conditioned building with flat-box-type thermal absorber and polycrystalline silicon cells, the year-round thermal and cell conversion efficiencies were found respectively to be 37.5% and 9.39% under typical Hong Kong weather conditions.

Dubey et al. [54] made an attempt to derive the analytical expressions for n hybrid photovoltaic/thermal air collectors connected in series. They showed the detailed analysis of energy, exergy and electrical energy by varying the number of collectors and air velocity considering four weather conditions and five different cities of India (New Delhi, Bangalore, Mumbai, Srinagar, and Jodhpur).

3. Opaque and passive solar facades

The opaque and passive solar facades may be a south wall or surface glaze that transform the incident sunlight into thermal energy, for heating or ventilation purposes of the building, without using electrical or mechanical equipment (pumps, fans, valves and control equipments).

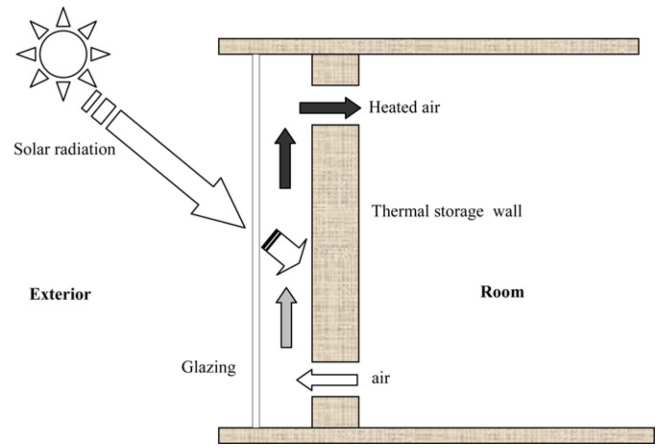


Fig. 6. Schematic diagram of thermal storage wall (e.g., Trombe wall).

3.1. Thermal storage wall

Thermal storage wall combines the functions of solar collector and storage into a single unit. Heat is transferred from the wall to the room air and to the air between glazing and wall, by radiation and natural convection. Reducing indoor air temperature swings is one of its principal functions (Fig. 6).

3.1.1. Theoretical and experimental study

Fang and Li [55] developed a three-dimensional transient heat transfer model of a lattice passive solar heating wall (LPSHW), based on which a computer simulation program was developed in FORTRAN language. The model predictions agreed quite well with experimental data. From the sensitivity analysis, the optimum configuration was thus obtained. Under the chosen conditions, thermal efficiency was 30.2% for the LPSHW and 22.6% for the Trombe wall. In a second paper, Fang and Yang [56] presented a new approach, regression analysis, and developed a general regression model. The lattice solar heating wall (LSHW) was selected as a case study. Detailed heat transfer analysis was performed to develop the specific regression model for the LSHW sensitivity analysis. The model was also used for LSHW optimization, yielding the same results as those from the simulation with the numerical simulation program, which further demonstrated that the proposed model was reliable.

Zalewski et al. [57] presented the results of a comparative study of four different types of solar wall. These results have been obtained using a numerical simulation model. To validate the model, an extensive experimental study has been conducted on a composite solar wall. The model was then used to study the energy efficiency of solar walls in different locations and under different climatic conditions.

Onbasioglu and Egrican [58] investigated the thermal performance of a passive solar heating system via simultaneous temperature, velocity and flux measurements and their acquisition. The sensor locations were on the walls and at the vents. Evaluation of the data using the definitions of the modified Rayleigh numbers concluded the existence of two extreme points. One of them represented the situation of the maximum amount of heat transfer to the test room. The second extreme situation was the beginning of the heat loss to the environment due to the reverse circulation process, namely night time cooling.

Stritih [59] studied the impact of paraffin as phase change material on heat transfer in solar heat storage wall. The mathematical model output was the time dynamics of heat accumulation in phase

change material with fins as the media for heat transport enhancement. It was found out that the most influential of the parameters was the distance between the fins.

Chen and Liu [60,61] studied the heat transfer and air flow in composite-wall solar-collector systems with porous absorber. The unsteady numerical simulation was employed to analyze the performances of the flow and temperature field in the composite solar walls. The influence of the particle size, the porosity, the thermal conductivity of porous layer and the porous absorber position in the solar composite wall on the air temperature in the heated room were significant.

Hernández et al. [62] proposed an analytical model to calculate the behavior of a heat discharge system in walls by simply knowing the dimensions of the prototype and the environmental conditions data. Six tests were carried out in the experimental model. In four of them, the heat flux simulation was performed with electrical resistors; in the other two, solar radiation was directly employed. The results show that the thermal performance of the system can be determined and described by the analytical model, within a small margin of error. In a subsequent study, Hernández et al. [63] presented the results obtained by modifying the design conditions of an in-wall heat discharge system, used to prevent the overheating of the controlled space. After making some variations to the analytical model, this study concluded that it is advisable to increase both the width of the system and the opening of the air channel intake, thus allowing for a greater flow of ventilation air within the system without overheating either the heat storage plate or the interior of the controlled space.

Thomas et al. [64] presented the results of a combined analytical, computational, and experimental study of the key parameters for selecting affordable materials and designing for thermal comfort in passive solar buildings. The simple analytical model of heat diffusion was used to identify the factor of merit for the optimization of affordable passive solar performance. The time dependence of wall/internal temperature was then simulated using a simple finite difference model.

Burek and Habeb [65] reported on a set of experiments conducted to measure the airflow and temperature profiles in a test rig designed to simulate the essential features of a Trombe Wall or solar chimney (SC). The results are presented in dimensionless form, based on parameters which are either known or controllable such as mass flow rate, heat input and channel depth.

Shen et al. [66] developed and validated a simulation model concerning the "composite" Trombe wall, which includes an insulating layer. They used the finite difference method and confronted the assumptions and the results of simulations with those of an existing module in TRNSYS (Type 36) established for the "classical" Trombe wall. Later, Shen et al. [67] studied the thermal performances of passive solar systems, a classical Trombe wall and a composite Trombe wall. The models were developed with the finite differences method and with TRNSYS software. The results showed that the models developed were very precise, and the composite wall had better energetic performances than the classical wall in cold and/or cloudy weather.

Zamora and Kaiser [68] obtained two-dimensional, laminar, transitional and turbulent simulations by solving the fully-elliptic governing equations of the motion established by natural convection in channels with Trombe wall configuration, for different geometrical parameters and symmetrical heating. To validate the numerical results, some comparisons with experimental results taken from literature have been carried out. Correlations for the thermal and the mass-flow optimum wall-to-wall spacing have been presented.

Ruiz-Pardo et al. [69] revised the European and International Standard UNE-EN ISO 13790 in order to check the proposed mathematical models and their implementation within Mediterranean climates. This assessment pinpointed the existence of some errors in the equations provided in EN ISO 13790 under steady state conditions. Concurrently, the corrected equations are shown and new correlations are proposed which are more suitable for Mediterranean climates.

3.1.2. Development

Bakos [70] described a simple control strategy, known as minimum-cost method, and determined its performance characteristics in a combined sunspace-Trombe Wall passive solar system. Furthermore, a specific application was studied for a residence heated using this solar collector and an electrically heated thermal storage floor to satisfy the heating requirements of the house.

Bilgen [71] studied experimentally the natural convection, radiation and conduction heat transfer in passive solar massive wall systems with fins attached to the heated surface and with glazing. A heat source was used to impose a constant heat flux which could be varied from about 200 to 800 W/m^2. Temperatures at various points and heat flux by convection at the back were measured. Using various assumptions, the system was also analyzed theoretically. The results showed that about 40% of the heat flux imposed on the finned surface goes through the system and is dissipated at the back.

Onishi et al. [72] numerically investigated basic performance of a hybrid heating system through several case studies including examinations of effects of PCM as a heat storing materials. A simple test room equipped with a Trombe wall was used. Simulated results indicated the effectiveness of PCM and suggested the possibility of developing low energy houses with hybrid system introduced in this study.

Tyagi and Buddhi [73] presented a comprehensive review of various possible methods for heating and cooling in buildings. The thermal performance of various types of systems like PCM Trombe wall, PCM wallboards, PCM shutters, PCM building blocks, air-based heating systems, floor heating, ceiling boards, etc. were discussed in this paper.

Nwachukwu and Okonkwo [74] undertook an analysis to show the effects of a range of coating absorptivity values on the improvement of heat transfer across a Trombe wall and to its enclosure. The analysis showed that enhanced heat delivery is feasible with the application of a better absorptive coating on the heat-receiving surface of the wall; characterized by high absorptivity and very low emissivity.

Pasupathy et al. [75] gathered the information from the earlier works on the developments of incorporation of phase change material in building (e.g., solar heat storage wall), the problems associated with the selection of PCM and the various methods used to contain them for space heating and cooling applications.

Sharma et al. [76] summarized the investigation and analysis of the available thermal energy storage systems incorporating phase change materials for heating and cooling applications of buildings.

Zhu et al. [77] presented an overview of the previous research work on dynamic characteristics and energy performance of buildings (e.g., solar heat storage wall) due to the integration of phase change materials.

Heim [78] analyzed a storage system with an encapsulated phase change materials. Numerical simulations were conducted for two cases of multi-zone, highly glazed and naturally ventilated passive solar buildings. Transparent insulation material (TIM) combined with PCM was applied for the external south-oriented wall in the second case study. The behaviour of a TIM-PCM wall and its influence on the internal surface temperature were estimated.

3.1.3. Feasibility study

Blasco et al. [79] studied the convenience of passive systems in a continental mediterranean climate. A comparative experimental

analysis on the thermal performance of three passive systems (massive/Trombe wall, direct gain and sunspace) was carried out. The massive/Trombe wall joined to the sunspace gave the best results.

Yang et al. [80] developed a simulation model to analyze the potential of the application of transparent insulation of honeycombed structures for passive solar buildings in northern China. By simulating the monthly auxiliary energy requirement of the building and the solar fraction variation due to transparent insulation, it was found that if the traditional south brick walls are covered by a 10 cm thickness layer of honeycomb material in the Beijing area, an increase in solar fraction will be around 39%, corresponding to a solar heat gain of around 137 Wh/m^2 per year.

Raman et al. [81] described the development of a solar passive system, which can provide thermal comfort throughout the year in composite climates with hot-dry, hot-humid and cold climatic conditions. In the first phase, passive model 1 comprising two sets of solar chimneys was developed. Based on the feedback and experience, an improved version of model 2 was developed. In model 2 both the Trombe wall and a roof duct wetted on the top side by an evaporatively-cooled surface were incorporated, in order to make the solar passive system more effective and also to give it a more compact and aesthetic appearance.

Kalogirou et al. [82] presented the effects on the heating and cooling load resulting from the use of building thermal mass in Cyprus. This was achieved by modelling and simulation with the TRNSYS program of a typical four-zone building with an insulated roof in which the south wall of one of the zones has been replaced by a thermal wall. The results of the simulation showed that there was a reduction in the heating load requirement of the zone by about 47%, whereas at the same time a slight increase of the zone-cooling load is exhibited.

Demirbilek et al. [83] thermally evaluated the Turkey's National Observatory guesthouse through different modes of application of insulation, materials, types of glazing, window/wall ratios, Trombe walls, winter night insulation, summer ventilation and shading.

Brunetti et al. [84] described and evaluated the contribution of energetic need provided by a Trombe-wall in relation to the acclimatisation of an environment. The applicability of innovative solutions capable of sustaining, energetically, autonomous electrical structures of rural and/or isolated premises was also investigated.

Evans [85] considered the need to define comfort of indoor and outdoor spaces in relation to the daily variations of temperature. A graphical tool was presented, which indicates the daily swings of temperature, shown as a single point on a graph representing the average temperature and the maximum temperature swing. The development of the graph was explained using the following example. On a typical sunny winter's day when the outdoor air temperature varies between 5 and 12 °C, the external conditions are well outside the comfort zone. But at the outer dark surface of the Trombe wall, behind the glass, the average temperature and the temperature range will increase significantly on sunny days, reaching 25 °C and 40 °C, respectively. By day, the surface temperature reaches 45 °C, but by night drops close to 5 °C. However, on the inside of the same mass wall, the high thermal inertia will dampen down the temperature swing, to an average temperature of 25 °C and a range of 4 °C. If the internal design temperature is 21 °C, then the surface temperature of this wall will never drop below this level and during most of the day will provide a useful source of heat to the interior.

Ballestini et al. [86] analysed a case study for investigating the possibility of application of passive solar systems in mediterranean climate on an abandoned silk factory, by means of dynamic simulations performed by coupling TRNSYS and LOOPDA simulation models. In this study, the old airflow patterns were maintained and, due to the sunspace in winter and the night-cooling in summer, 12% of the energy needed for cooling and heating might be saved over a year.

Chen et al. [87] conducted some experiments on the thermal performance of an advanced Trombe wall with shading in the air gap in a passive solar house in Dalian, Northeast China. The thermal performance was investigated with regard to the simultaneous temperatures, heat gain and their acquisition of the Trombe wall. Finally, the influence of shading on improving indoor thermal comfort was discussed using the concept of the building envelope response factor. Later, the same team, Chen et al. [88] conducted two field surveys in three residences to investigate the thermal environments of rural residences with a coupled Chinese elevated kang and passive solar collecting wall heating system. A Chinese kang is a rectangular platform with the materials of brick, slate, concrete or clay used as thermal storage mass. Indoor thermal environments were evaluated with parameters of indoor air temperature and relative humidity, surface temperature of the kang plates, air temperature of the upper/lower vents in passive solar wall and human activities.

Chandel and Aggarwal [89] evaluated the thermal performance of a passive solar bank building at Shimla. This solar building incorporates a heat-collecting wall and a roof-top solar air heater with an electric heating backup, sunspaces and double-glazed windows. It was shown that the solar passive features save electricity required for space heating and reduce the heat loss in the building by about 35%.

Chel et al. [90] investigated energy conservation, mitigation of CO_2 emissions and economics of retrofitting for a honey storage building with Trombe wall for winter heating application. The passive heating potential of Trombe wall for a honey storage building was estimated using TRNSYS building simulation software. This honey storage building is located at Gwalior in India. This investigation concluded that there was potential of energy conservation up to 3312 kWh/year and associated reduction in CO_2 emissions (~33 tonnes/year) using a Trombe wall.

Yilmaz and Basak Kundakci [91] recommended to renovate the south facade of a flat in an existing building in Istanbul by the application of Trombe wall principle. An approach was proposed for this application and the comparison of the existing facade with the renovated facades has been made according to thermal performances and hourly variations of wall interior temperatures.

Khalifa and Abbas [92] conducted a numerical study on a zone heated by a thermal storage wall. Three different storage materials were examined, namely concrete, the hydrated salt $CaCl_2{\cdot}6H_2O$ and paraffin wax (*n*-eicosane). The study concluded that an 8-cm-thick storage wall made from the hydrated salt is capable of maintaining the comfort temperature in the zone with the least room temperature fluctuation.

Ji et al. [93] proposed an improved Trombe wall to adapt to building construction with selective thermo-insulation facades (internal and cavity wall insulation, but not external wall insulation system). The case study is conducted in Xining, China. The operating efficiency of the improved Trombe wall could be up to 33.85%, an increase of 56% from that of the classical Trombe wall system. The results showed that the improved Trombe wall works more effectively than the classical Trombe wall system in utilizing solar energy for the sample building.

Nwosu [94] proposed a hemispherical, passive design for a poultry brooding enterprise for the equatorial climatic belt. An analysis was undertaken of the heat transfer balance across the wall. It was found that improvement in the absorptive and storage capacity of the wall is enhanced with high absorptive coating quality.

3.1.4. Application example

Voss [95] summarised the cross-analysis of the demonstration projects, evaluated between 1995 and 1998. The analysis covered

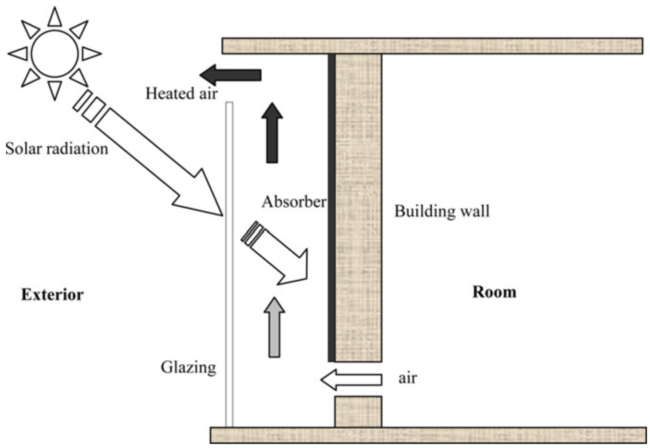


Fig. 7. Schematic diagram of solar chimney.

technical, economic, and building physic issues of solar collectors, glazed balconies, and solar walls.

3.2. *Solar chimney*

A solar chimney is a structure that consists mainly of one heat-absorbing glazed surface and it is constructed on the wall facing the direction of the sun. When solar energy heats the chimney and the air within it, it produces an updraft of air in the chimney. The natural aspiration created at the chimney's base can be used to ventilate the building (Fig. 7).

3.2.1. *Theoretical and experimental study*

Afonso and Oliveira [96] carried out experimental tests to compare the contribution of a solar chimney and a conventional chimney to the natural ventilation of buildings. Results of measurements in both chimneys are shown, as well as results of a thermal model specially developed for simulating solar chimneys, taking into account the wind effect. It was concluded that there is a significant increase in ventilation rate with solar chimneys, and that the thermal model predicts with good accuracy the measurements carried out.

Ong [97] proposed a simple mathematical model of a solar chimney. The physical model is similar to that of the Trombe wall. The equations were solved using a matrix-inversion solution procedure. The thermal performance of the solar chimney as determined from the glass, wall and air temperatures, air mass flow rate and instantaneous heat collection efficiency of the chimney are presented. Satisfactory correlation was obtained with experimental data from other investigators. Later, Ong and Chow [98] proposed a mathematical model of a solar chimney to predict its performance under varying ambient and geometrical features. Steady state heat transfer equations were set up using a thermal resistance network and solved using matrix inversion. The effects of air gap and solar radiation intensity on the performance of different chimneys were investigated. Air velocities between 0.25 m/s and 0.39 m/s for radiation intensity up to 650 W/m^2 were obtained. No reverse air flow circulation was observed even at the large gap of 0.3 m.

Bansal et al. [99] developed a mathematical model for predicting airflow velocity in a solar chimney. Investigations have been carried out with three different combinations of air gap and size of the inlet opening for entry of air in the chimney. Good agreement between observed and calculated results has been obtained. The small size of the analyzed solar chimney has opened possibilities of utilizing windows as solar chimneys since the flow velocity up to 0.24 m/s has been experimentally recorded.

Gan [100] used the commercial computational fluid dynamics (CFD) package FLUENT to predict buoyant air flow and flow rates in the cavities. The CFD model was validated against measured data from the literature and good agreement between the prediction and measurement was achieved. It was found that there existed an optimum cavity width for maximising the buoyancy-induced flow rate and the optimum width was between 0.55 and 0.6 m for a solar chimney of 6 m high.

Mathur et al. [101] presented work based upon the theoretical modeling and experimental validation studies conducted on small size solar chimneys specially having an absorber length less than 1 m. The developed experimental set-up was a cubical wooden chamber having a size of 1 m × 1 m × 1 m. Nine different combinations of absorber heights and air gaps have been investigated on the experimental set-up. The highest rate of ventilation induced with the help of solar energy was found to be 5.6 air changes per hour in a room of 27 m^3, at solar radiation 700 W/m^2 on vertical surface with the stack height-air gap ratio of 2.83 for a 1 m high chimney.

Nouanégué et al. [102] carried out a numerical study of a simplified system of solar-wind tower for ventilation of dwellings. The conservation equations for mass, momentum and energy for mixed convection in two-dimensional coordinates are solved by the control volume method and Simpler (semi-implicit method for pressure linked equations revised) algorithm. The results showed that the important parameters affecting the ventilation performance are the Rayleigh number, the Reynolds number (or Richardson number) and the geometrical parameters. In another paper, Nouanégué and Bilgen [103] carried out a numerical study by conjugate heat transfer of solar chimney systems for heating and ventilation of dwellings. Conservation equations are solved by finite difference-control volume numerical method. The results showed that the surface radiation modifies the flow and temperature fields, affects the Nusselt number and the volume flow rate, both in a positive way, and improves the ventilation performance of the chimneys.

Sakonidou et al. [104] developed a mathematical model to determine the tilt angle that maximizes natural air flow inside a solar chimney using daily solar irradiance data on a horizontal plane. The model predicts the temperature and velocity of the air inside the chimney as well as the temperatures of the glazing and the black painted absorber. There was a good agreement between theoretical predictions and experiments performed with a 1 m long solar chimney at different tilt positions.

Zamora and Kaiser [105] performed a numerical study on the laminar and turbulent flows induced by natural convection in channels, with solar chimney configuration, for a wide range of Rayleigh number (Ra_L), several values of the relative wall-to-wall spacing and different heating conditions. It has been obtained a correlation for the thermal optimum aspect ratio $(b/L)_{opt}$ that maximizes Nu_L at vertical walls in channels with solar chimney geometry, for $10^5 \leq Ra_L \leq 10^{12}$ and symmetrically isothermal heating conditions. The higher value of Ra_L, the lower value of $(b/L)_{opt}$. In a subsequent study, Zamora and Kaiser [106] obtained numerical results for the pressure difference coefficients, average Nusselt number (Nu) and the induced mass flow rate for values of Rayleigh number varying from 10^7 to 10^{12} (symmetrically, isothermal heating condition) and 10^{11} to 10^{15} (symmetrically, uniform heat flux heating condition), with wind speeds from 0 to 10 m/s and assuming that the chimney is devoid of any protective device at its upper part. A correlation for the non-dimensional mass flow rate was presented, which was valid for the complete range of relevant parameters regarded, with an average deviation about 6%.

3.2.2. *Development*

Harris and Helwig [107] investigated the design of a solar chimney to induce ventilation in a building. The conditions used in their

study were for Edinburgh in Scotland at latitude 52°. CFD modelling techniques were used to assess the impacts of inclination angle, double glazing and low-emissivity coatings on the induced ventilation rate. It was found that for a south-facing chimney located at the roof, an inclination angle of 67.5° from the horizontal was optimum, giving 11% greater efficiency than the vertical chimney, and that a 10% higher efficiency was obtained by using a low-emissivity wall surface.

3.2.3. Feasibility study

Khedari et al. [108] investigated, experimentally, both the feasibility of a solar chimney to reduce heat gain in a house by natural ventilation and the effect of openings (door, window and inlet of solar chimney) on the ventilation rate. The study was conducted using a single-room test house of approximately 25 m^3 volume. The southern wall was composed of three different solar chimney configurations of 2 m^2 each, whereas, the roof southern side included two similar units of 1.5 m^2 each of another solar chimney configuration. Experimental observations indicated that when the solar chimney ventilation system was in use, room temperature was near that of the ambient air, indicating a good ability of the solar chimney to remove heat gain in the house and ensuring thermal comfort. The air change rate varied between 8 and 15 air changes per hour. In a following paper, Khedari et al. [109] examined the performance of a solar chimney within an air-conditioned building. To this end, a single-room house of 25 m^3 volume was used. Two configurations of SC were used. Experiments were performed throughout a period of six months (March–September). Comparisons between a common house and a solar chimney house conducted using days with relatively similar ambient conditions demonstrated that a SC house could reduce the cooling average daily electrical consumption by 10–20%. In that case, the appropriate size of inlet openings of a SC is 5 cm × 5 cm, which induces about 3–8 m^3/h per solar chimney.

Imessad et al. [110] studied the Barra–Costantini passive solar heating system, with particular emphasis on the aspect of economics. The Barra–Costantini system is based on an air collector technique with the installation of an absorber between a wall and glazing, in order to benefit from double natural circulation. An ideal model representing the thermal behavior of a room provided with the heating device was elaborated. The results of this model were compared with the results of an experimental study carried out on an Italian site, showing that the interior room temperature variation with time did not exceed 2 °C and that the ceiling temperature had a difference of 1 °C the first day before reaching perfect agreement on the other days. The model was then used for conditions corresponding to several Algerian sites.

Miyazaki et al. [111] investigated the performance of a solar chimney, which is integrated into a south facade of a one-storey building, as well as the effect on the heating and cooling loads of the building by using a CFD simulation and an analytical model. A C programming code was developed for the calculation of the heating and cooling loads by the heat balance method. The results showed that the fan shaft power requirement was reduced by about 50% over a year due to the natural ventilation. It was also found that the solar chimney reduced the heating load by about 20% during the heating season. The annual thermal load mitigation was estimated as 12% by taking into account the increase of the cooling load.

Martí et al. [112] investigated the theoretical usefulness of a solar chimney with thermal inertia applied to the mediterranean climates, offering nocturnal ventilation benefits. A mathematical dynamical model is proposed to evaluate the energy performance of a solar chimney with a 24 cm thick concrete wall as storage surface for solar radiation. The results showed that for a 2 m height and width of air channel of 14.5 cm thickness, 0.011 kg/s air mass flow rate is obtained for 450 W/m^2. The 24 cm thick concrete wall reached its higher temperature 2 h later than the ambient temperature, maintaining its temperature widely above the ambient temperature when solar radiation no longer exists. As a consequence, nocturnal natural ventilation is produced, which is very interesting for Mediterranean climates with very warm nights.

Punyasompun et al. [113] presented an investigation on the use of solar chimneys in high-rise buildings. To this end, two small scale models of a three storey building were built. The floor dimensions of each storey are 1.2 m × 2 m × 1 m. Solar chimneys were integrated into the south-faced walls of one unit whereas the other unit served as a reference. Reasonable agreement between the experimental data and those derived from the mathematical model developed using electric analogies was obtained.

Lee and Strand [114] developed a new module and implemented it in the EnergyPlus program for the simulation and determination of the energy impact of thermal chimneys. Using the new module, the effects of the chimney height, solar absorptance of the absorber wall, solar transmittance of the glass cover and the air gap width were investigated under various conditions. The potential energy impacts of a thermal chimney under three different climate conditions are also investigated. Chimney height, solar absorbance and solar transmittance turned out to have more influence on the ventilation enhancement than the air gap width. In addition, the performance of a thermal chimney was heavily dependent on the climate of the location.

4. Conclusions

A detailed literature survey of studies carried out during the last 10 years in opaque solar facades has been performed. The studies reviewed were grouped into the following five systems: building-integrated solar thermal, building-integrated photovoltaic, building-integrated photovoltaic thermal, thermal storage wall and solar chimney.

Building-integrated solar thermal technology certainly presents an interest since it is a relatively simple technology. Still it is not yet fully optimized. For example, the impact of wind is not yet well understood. Nevertheless, new coatings are now extending the versatility of this technology.

Building-integrated photovoltaic offers many advantages. They can produce a significant amount of energy, which in the best conditions can even exceed the buildings internal consumption. In addition, in some configurations PV wall can significantly reduce cooling loads. Also in some designs, the air flow behind the PV panel can both cool them, which improves their efficiency and reduces the heat load on the building.

Hybrid thermal/PV systems combine the advantages of both PV and solar thermal building integrated systems. Heat extraction by the thermal component improves the PV efficiency. This synergetic effect largely improves the economic return of the PV system by adding the thermal output to its function.

The most developed system is the thermal storage wall and its variants. These systems have demonstrated their potential for the reduction of the heating load (40–50%) consistently. The technology is advanced enough that a European and International Standard UNE-EN ISO 13790 exist to perform calculations describing their thermal behavior.

While similar to the Trombe wall, the solar chimney is a less advanced technology. Some energy efficiency gains are expected. However, there is still significant potential for optimization.

In regard to these results, this study showed that all these technologies are promising. However, more studies are needed to bring them to their optimum performance. Only the thermal storage wall and its variants can claim this feat now.

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References

[1] Van Decker GWE, Hollands KGT, Brunger AP. Heat-exchange relations for unglazed transpired solar collectors with circular holes on a square or triangular pitch. Solar Energy 2001;71:33–45.
[2] Fleck BA, Meier RM, Matovic MD. A field study of the wind effects on the performance of an unglazed transpired solar collector. Solar Energy 2002;73:209–16.
[3] Gunnewiek LH, Hollands KGT, Brundrett E. Effect of wind on flow distribution in unglazed transpired-plate collectors. Solar Energy 2002;72:317–25.
[4] Leon MA, Kumar S. Mathematical modeling and thermal performance analysis of unglazed transpired solar collectors. Solar Energy 2007;81:62–75.
[5] Boutin Y, Gosselin L. Optimal mixed convection for maximal energy recovery with vertical porous channel (solar wall). Renewable Energy 2009;34:2714–21.
[6] Richman RC, Pressnail KD. A more sustainable curtain wall system: analytical modeling of the solar dynamic buffer zone (SDBZ) curtain wall. Building and Environment 2009;44:1–10.
[7] Richman R, Pressnail KD. Quantifying and predicting performance of the solar dynamic buffer zone (SDBZ) curtain wall through experimentation and numerical modeling. Energy and Buildings 2010;42:522–33.
[8] Orel B, Spreizer H, Surca Vuk A, Fir M, Merlini D, Vodlan M, Köhl M. Selective paint coatings for coloured solar absorbers: polyurethane thickness insensitive spectrally selective (TISS) paints (Part II). Solar Energy Materials and Solar Cells 2007;91:108–19.
[9] Japelj B, Vuk AS, Orel B, Perse LS, Jerman I, Kovac J. Preparation of a TiMEMO nanocomposite by the sol–gel method and its application in coloured thickness insensitive spectrally selective (TISS) coatings. Solar Energy Materials and Solar Cells 2008;92:1149–61.
[10] Kozelj M, Vuk AS, Jerman I, Orel B. Corrosion protection of Sunselect, a spectrally selective solar absorber coating, by (3-mercaptopropyl)trimethoxysilane. Solar Energy Materials and Solar Cells 2009;93:1733–42.
[11] Jerman I, Kozelj M, Orel B. The effect of polyhedral oligomeric silsesquioxane dispersant and low surface energy additives on spectrally selective paint coatings with self-cleaning properties. Solar Energy Materials and Solar Cells 2010;94:232–45.
[12] Ubertini S, Desideri U. Design of a solar collector for year-round climatization. Renewable Energy 2003;28:623–45.
[13] Fraisse G, Johannes K, Trillat-Berdal V, Achard G. The use of a heavy internal wall with a ventilated air gap to store solar energy and improve summer comfort in timber frame houses. Energy and Buildings 2006;38:293–302.
[14] Munari Probst M, Roecker C. Towards an improved architectural quality of building integrated solar thermal systems (BIST). Solar Energy 2007;81:1104–16.
[15] Hernández AL, Lesino G, Rodríguez L, Linares J. Design, modelling and computational assessment of passive and active solar collectors for thermal conditioning of the first bioclimatic hospital in Argentina. Journal of Building Performance Simulation 2009.
[16] Henemann A. BIPV: built-in solar energy. Renewable Energy Focus 2008;9(14):16–9.
[17] Brinkworth BJ, Marshall RH, Ibarahim Z. A validated model of naturally ventilated PV cladding. Solar Energy 2000;69:67–81.
[18] Yang H, Burnett J, Ji J. Simple approach to cooling load component calculation through PV walls. Energy and Buildings 2000;31:285–90.
[19] Chow TT, Hand JW, Strachan PA. Building-integrated photovoltaic and thermal applications in a subtropical hotel building. Applied Thermal Engineering 2003;23:2035–49.
[20] Huang MJ, Eames PC, Norton B. Thermal regulation of building-integrated photovoltaics using phase change materials. International Journal of Heat and Mass Transfer 2004;47:2715–33.
[21] Huang MJ, Eames PC, Norton B. Phase change materials for limiting temperature rise in building integrated photovoltaics. Solar Energy 2006;80:1121–30.
[22] Bloem JJ. Evaluation of a PV-integrated building application in a well-controlled outdoor test environment. Building and Environment 2008;43:205–16.
[23] Fossa M, Ménézo C, Leonardi E. Experimental natural convection on vertical surfaces for building integrated photovoltaic (BIPV) applications. Experimental Thermal and Fluid Science 2008;32:980–90.
[24] Jiménez MJ, Madsen H, Bloem JJ, Dammann B. Estimation of non-linear continuous time models for the heat exchange dynamics of building integrated photovoltaic modules. Energy and Buildings 2008;40:157–67.
[25] Friling N, Jiménez MJ, Bloem H, Madsen H. Modelling the heat dynamics of building integrated and ventilated photovoltaic modules. Energy and Buildings 2009;41:1051–7.
[26] Maurus H, Schmid M, Blersch B, Lechner P, Schade H. PV for buildings: benefits and experiences with amorphous silicon in BIPV applications. Refocus 2004;5:22–7.
[27] Mallick TK, Eames PC, Norton B. Non-concentrating and asymmetric compound parabolic concentrating building facade integrated photovoltaics: an experimental comparison. Solar Energy 2006;80:834–49.
[28] Jie J, Wei H, Lam HN. The annual analysis of the power output and heat gain of a PV-wall with different integration mode in Hong Kong. Solar Energy Materials and Solar Cells 2002;71:435–48.
[29] Ordenes M, Marinoski DL, Braun P, Rüther R. The impact of building-integrated photovoltaics on the energy demand of multi-family dwellings in Brazil. Energy and Buildings 2007;39:629–42.
[30] Abu-Rub H, Iqbal A, Amin S, Abdelkadar G, Salem N, Mansoor S, Mirza T, Ahmed S. Feasibility analysis of solar photovoltaic array cladding on commercial towers in Doha, Qatar – a case study. International Journal of Sustainable Energy 2010;29:76–86.
[31] Omer SA, Wilson R, Riffat SB. Monitoring results of two examples of building integrated PV (BIPV) systems in the UK. Renewable Energy 2003;28:1387–99.
[32] Yang H, Zheng G, Lou C, An D, Burnett J. Grid-connected building-integrated photovoltaics: a Hong Kong case study. Solar Energy 2004;76:55–9.
[33] Marsh G. BIPV: innovation puts spotlight on solar. Renewable Energy Focus 2008;9:62–7.
[34] Ji J, Han J, Chow T-t, Yi H, Lu J, He W, Sun W. Effect of fluid flow and packing factor on energy performance of a wall-mounted hybrid photovoltaic/water-heating collector system. Energy and Buildings 2006;38:1380–7.
[35] Muresan C, Ménézo C, Bennacer R, Vaillon R. Numerical simulation of a vertical solar collector integrated in a building frame: radiation and turbulent natural convection coupling. Heat Transfer Engineering 2006;27:29–42.
[36] Chow TT, He W, Ji J. An experimental study of facade-integrated photovoltaic/water-heating system. Applied Thermal Engineering 2007;27:37–45.
[37] Jie J, Hua Y, Wei H, Gang P, Jianping L, Bin J. Modeling of a novel Trombe wall with PV cells. Building and Environment 2007;42:1544–52.
[38] Jie J, Hua Y, Gang P, Jianping L. Study of PV-Trombe wall installed in a fenestrated room with heat storage. Applied Thermal Engineering 2007;27:1507–15.
[39] Jie J, Hua Y, Gang P, Bin J, Wei H. Study of PV-Trombe wall assisted with DC fan. Building and Environment 2007;42:3529–39.
[40] Tonui JK, Tripanagnostopoulos Y. Air-cooled PV/T solar collectors with low cost performance improvements. Solar Energy 2007;81:498–511.
[41] Tonui JK, Tripanagnostopoulos Y. Improved PV/T solar collectors with heat extraction by forced or natural air circulation. Renewable Energy 2007;32:623–37.
[42] Tonui JK, Tripanagnostopoulos Y. Performance improvement of PV/T solar collectors with natural air flow operation. Solar Energy 2008;82:1–12.
[43] Dehra H. A two dimensional thermal network model for a photovoltaic solar wall. Solar Energy 2009;83:1933–42.
[44] Radziemska E. Thermal performance of Si and GaAs based solar cells and modules: a review. Progress in Energy and Combustion Science 2003;29:407–24.
[45] Tripanagnostopoulos Y. Aspects and improvements of hybrid photovoltaic/thermal solar energy systems. Solar Energy 2007;81:1117–31.
[46] Zondag HA. Flat-plate PV-thermal collectors and systems: a review. Renewable and Sustainable Energy Reviews 2008;12:891–959.
[47] Hasan MA, Sumathy K. Photovoltaic thermal module concepts and their performance analysis: a review. Renewable and Sustainable Energy Reviews 2010;14:1845–59.
[48] Norton B, Eames PC, Mallick TK, Huang MJ, McCormack SJ, Mondol JD, et al. Enhancing the performance of building integrated photovoltaics. Solar Energy 2011;85:1629–64.
[49] Chow TT. A review on photovoltaic/thermal hybrid solar technology. Applied Energy 2010;87:365–79.
[50] Ji J, Chow T-T, He W. Dynamic performance of hybrid photovoltaic/thermal collector wall in Hong Kong. Building and Environment 2003;38:1327–34.
[51] Crawford RH, Treloar GJ, Fuller RJ, Bazilian M. Life-cycle energy analysis of building integrated photovoltaic systems (BiPVs) with heat recovery unit. Renewable and Sustainable Energy Reviews 2006;10:559–75.
[52] Guiavarch A, Peuportier B. Photovoltaic collectors efficiency according to their integration in buildings. Solar Energy 2006;80:65–77.
[53] Chow TT, Chan ALS, Fong KF, Lin Z, He W, Ji J. Annual performance of building-integrated photovoltaic/water-heating system for warm climate application. Applied Energy 2009;86:689–96.
[54] Dubey S, Solanki SC, Tiwari A. Energy and exergy analysis of PV/T air collectors connected in series. Energy and Buildings 2009;41:863–70.
[55] Fang X, Li Y. Numerical simulation and sensitivity analysis of lattice passive solar heating walls. Solar Energy 2000;69:55–66.
[56] Fang X, Yang T. Regression methodology for sensitivity analysis of solar heating walls. Applied Thermal Engineering 2008;28:2289–94.
[57] Zalewski L, Lassue S, Duthoit B, Butez M. Study of solar walls – validating a simulation model. Building and Environment 2002;37:109–21.
[58] Onbasioglu H, Egrican AN. Experimental approach to the thermal response of passive systems. Energy Conversion and Management 2002;43:2053–65.
[59] Stritih U. Heat transfer enhancement in latent heat thermal storage system for buildings. Energy and Buildings 2003;35:1097–104.
[60] Chen W, Liu W. Numerical analysis of heat transfer in a composite wall solar-collector system with a porous absorber. Applied Energy 2004;78:137–49.

[61] Chen W, Liu W. Numerical analysis of heat transfer in a passive solar composite wall with porous absorber. Applied Thermal Engineering 2008;28:1251–8.
[62] Hernández V, Morillón D, Best JFR, Almanza R, Chargoy N. Experimental and numerical model of wall like solar heat discharge passive system. Applied Thermal Engineering 2006;26:2464–9.
[63] Hernández Gómez VH, Gálvez DM, Fernández Zayas JL. Design recommendations for heat discharge systems in walls. Applied Thermal Engineering 2010;30:1616–20.
[64] Thomas J, Algohary S, Hammad F, Soboyejo W. Materials selection for thermal comfort in passive solar buildings. Journal of Materials Science 2006;41:6897–907.
[65] Burek SAM, Habeb A. Air flow and thermal efficiency characteristics in solar chimneys and Trombe Walls. Energy and Buildings 2007;39:128–35.
[66] Shen J, Lassue S, Zalewski L, Huang D. Numerical study of classical and composite solar walls by TRNSYS. Journal of Thermal Science 2007;16:46–55.
[67] Shen J, Lassue S, Zalewski L, Huang D. Numerical study on thermal behavior of classical or composite Trombe solar walls. Energy and Buildings 2007;39:962–74.
[68] Zamora B, Kaiser AS. Thermal and dynamic optimization of the convective flow in Trombe Wall shaped channels by numerical investigation. Heat and Mass Transfer 2009;45:1393–407.
[69] Ruiz-Pardo Á, Domínguez SÁ, Fernández JAS. Revision of the Trombe wall calculation method proposed by UNE-EN ISO 13790. Energy and Buildings 2010;42:763–73.
[70] Bakos G. Energy management method for auxiliary energy saving in a passive-solar-heated residence using low-cost off-peak electricity. Energy and Buildings 2000;31:237–41.
[71] Bilgen E. Experimental study of massive wall systems with fins attached on the heated wall and with glazing. Heat and Mass Transfer 2001;38:159–64.
[72] Onishi J, Soeda H, Mizuno M. Numerical study on a low energy architecture based upon distributed heat storage system. Renewable Energy 2001;22:61–6.
[73] Tyagi VV, Buddhi D. PCM thermal storage in buildings: a state of art. Renewable and Sustainable Energy Reviews 2007;11:1146–66.
[74] Nwachukwu NP, Okonkwo WI. Effect of an absorptive coating on solar energy storage in a Trombe wall system. Energy and Buildings 2008;40:371–4.
[75] Pasupathy A, Velraj R, Seeniraj RV. Phase change material-based building architecture for thermal management in residential and commercial establishments. Renewable and Sustainable Energy Reviews 2008;12:39–64.
[76] Sharma A, Tyagi VV, Chen CR, Buddhi D. Review on thermal energy storage with phase change materials and applications. Renewable and Sustainable Energy Reviews 2009;13:318–45.
[77] Zhu N, Ma Z, Wang S. Dynamic characteristics and energy performance of buildings using phase change materials: a review. Energy Conversion and Management 2009;50:3169–81.
[78] Heim D. Isothermal storage of solar energy in building construction. Renewable Energy 2010;35:788–96.
[79] Blasco Lucas I, Hoesé L, Pontoriero D. Experimental study of passive systems thermal performance. Renewable Energy 2000;19:39–45.
[80] Yang H, Zhu Z, Burnett J. Simulation of the behaviour of transparent insulation materials in buildings in northern China. Applied Energy 2000;67:293–306.
[81] Raman P, Mande S, Kishore VVN. A passive solar system for thermal comfort conditioning of buildings in composite climates. Solar Energy 2001;70:319–29.
[82] Kalogirou SA, Florides G, Tassou S. Energy analysis of buildings employing thermal mass in Cyprus. Renewable Energy 2002;27:353–68.
[83] Demirbilek FN, Yalciner UG, Ecevit A, Sahmali E, Inanici M. Analysis of the thermal performance of a building design located at 2465 m: Antalya-Saklikent National Observatory guesthouse. Building and Environment 2003;38:177–84.
[84] Brunetti L, Fucci F, La Fianza G, Libertone G. Renewable and integrative sources of energy: aspects and technological applications: evaluation of the contribution to the energetic needs provided by the passive solar system. Energy and Buildings 2003;35:763–74.
[85] Evans JM. Evaluating comfort with varying temperatures: a graphic design tool. Energy and Buildings 2003;35:87–93.
[86] Ballestini G, Carli MD, Masiero N, Tombola G. Possibilities and limitations of natural ventilation in restored industrial archaeology buildings with a double-skin facade in Mediterranean climates. Building and Environment 2005;40:983–95.
[87] Chen B, Chen X, Ding YH, Jia X. Shading effects on the winter thermal performance of the Trombe wall air gap: an experimental study in Dalian. Renewable Energy 2006;31:1961–71.
[88] Chen B, Zhuang Z, Chen X, Jia X. Field survey on indoor thermal environment of rural residences with coupled Chinese kang and passive solar collecting wall heating in Northeast China. Solar Energy 2007;81:781–90.
[89] Chandel SS, Aggarwal RK. Performance evaluation of a passive solar building in Western Himalayas. Renewable Energy 2008;33:2166–73.
[90] Chel A, Nayak JK, Kaushik G. Energy conservation in honey storage building using Trombe wall. Energy and Buildings 2008;40:1643–50.
[91] Yilmaz Z, Basak Kundakci A. An approach for energy conscious renovation of residential buildings in Istanbul by Trombe wall system. Building and Environment 2008;43:508–17.
[92] Khalifa AJN, Abbas EF. A comparative performance study of some thermal storage materials used for solar space heating. Energy and Buildings 2009;41:407–15.
[93] Ji J, Luo C, Sun W, Yu H, He W, Pei G. An improved approach for the application of Trombe wall system to building construction with selective thermo-insulation facades. Chinese Science Bulletin 2009;54:1949–56.
[94] Nwosu NP. Trombe wall redesign for a poultry chick brooding application in the equatorial region – analysis of the thermal performance of the system using the Galerkin finite elements. International Journal of Sustainable Energy 2010;29:37–47.
[95] Voss K. Solar energy in building renovation – results and experience of international demonstration buildings. Energy and Buildings 2000;32:291–302.
[96] Afonso C, Oliveira A. Solar chimneys: simulation and experiment. Energy and Buildings 2000;32:71–9.
[97] Ong KS. A mathematical model of a solar chimney. Renewable Energy 2003;28:1047–60.
[98] Ong KS, Chow CC. Performance of a solar chimney. Solar Energy 2003;74:1–17.
[99] Bansal NK, Mathur J, Mathur S, Jain M. Modeling of window-sized solar chimneys for ventilation. Building and Environment 2005;40:1302–8.
[100] Gan G. Simulation of buoyancy-induced flow in open cavities for natural ventilation. Energy and Buildings 2006;38:410–20.
[101] Mathur J, Bansal NK, Mathur S, Jain M, Anupma. Experimental investigations on solar chimney for room ventilation. Solar Energy 2006;80:927–35.
[102] Nouanégué HF, Alandji LR, Bilgen E. Numerical study of solar-wind tower systems for ventilation of dwellings. Renewable Energy 2008;33:434–43.
[103] Nouanégué HF, Bilgen E. Heat transfer by convection, conduction and radiation in solar chimney systems for ventilation of dwellings. International Journal of Heat and Fluid Flow 2009;30:150–7.
[104] Sakonidou EP, Karapantsios TD, Balouktsis AI, Chassapis D. Modeling of the optimum tilt of a solar chimney for maximum air flow. Solar Energy 2008;82:80–94.
[105] Zamora B, Kaiser AS. Optimum wall-to-wall spacing in solar chimney shaped channels in natural convection by numerical investigation. Applied Thermal Engineering 2009;29:762–9.
[106] Zamora B, Kaiser AS. Numerical study on mixed buoyancy-wind driving induced flow in a solar chimney for building ventilation. Renewable Energy 2010;35:2080–8.
[107] Harris DJ, Helwig N. Solar chimney and building ventilation. Applied Energy 2007;84:135–46.
[108] Khedari J, Boonsri B, Hirunlabh J. Ventilation impact of a solar chimney on indoor temperature fluctuation and air change in a school building. Energy and Buildings 2000;32:89–93.
[109] Khedari J, Rachapradit N, Hirunlabh J. Field study of performance of solar chimney with air-conditioned building. Energy 2003;28:1099–114.
[110] Imessad K, Messaoudene NA, Belhamel M. Performances of the Barra–Costantini passive heating system under Algerian climate conditions. Renewable Energy 2004;29:357–67.
[111] Miyazaki T, Akisawa A, Kashiwagi T. The effects of solar chimneys on thermal load mitigation of office buildings under the Japanese climate. Renewable Energy 2006;31:987–1010.
[112] MartIĭ-Herrero J, Heras-Celemin MR. Dynamic physical model for a solar chimney. Solar Energy 2007;81:614–22.
[113] Punyasompun S, Hirunlabh J, Khedari J, Zeghmati B. Investigation on the application of solar chimney for multi-storey buildings. Renewable Energy 2009;34:2545–61.
[114] Lee KH, Strand RK. Enhancement of natural ventilation in buildings using a thermal chimney. Energy and Buildings 2009;41:615–21.